UCRL- 93582
PREPRINT

VIII. SUMMARY COMMENTS ON THE STATE OF STELLAR WIND THEORY AS IT RELATES TO NON-RADIAL PULSATIONS

John I. Castor

This paper prepared for submittal to
PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF
THE PACIFIC

November 1, 1985

VIII. SUMMARY COMMENTS ON THE STATE OF STELLAR WIND THEORY AS IT RELATES TO NON-RADIAL PULSATIONS

John I. Castor

University of California, Lawrence Livermore National Laboratory
P.O. Box 808 / L-23
Livermore, California 94550

Running head: Stellar wind theory and NRP

Send proofs to: John I. Castor, Lawrence Livermore National Laboratory
University of California, P.O. Box 808 / L-23,
Livermore CA 94550

Key words: -- stellar wind theory -- wind instabilities -- pulsation

---

Invited paper presented at the workshop "The connection between nonradial pulsations and stellar winds in massive stars" held in Boulder, Colorado, April 17-19, 1985.

The radiatively-driven wind theory of Castor, Abbott and Klein (1975) has, in the last few years, received some embellishments that have improved its agreement with observations of O star winds and answered some questions that were raised about its approximations. These improvements include the work of Abbott (1982), who replaced the CAK power-law distribution of line strengths with a very complete tabulation of driving lines of many elements, combined with approximate non-LTE ionization balance. Another improvement was the replacement of the assumed point source of radiation with the correct finite-angle photospheric source; this was first considered by Abbott (1977) and was implicit in the later work of Weber (1981), Friend and Castor (1983) and Castor and Weber (1985, in preparation). This correction flattens the rather steep CAK velocity law and also raises the terminal velocity, both of which improve the agreement with observation.

Further developments have included the study of multi-line scattering (cf., Castor, 1979; Panagia and Macchetto, 1982). Self-consistent wind models allowing for multi-line scattering within the framework of a random spectral distribution of lines were made by Friend and Castor (1983), and calculations of mass-loss rate for multi-line scattering, assuming the velocity law but using the true distribution of lines, were made using a monte-carlo technique by Abbott and Lucy (1985). These models have shown that the mass-loss rate is not at all limited to the so-called single-scattering mass-loss rate, $L/v_\infty c$. The effect of stellar rotation and a stellar magnetic field have been considered by Friend and MacGregor (1984). They found that both effects enhance the mass loss, although magnetically-enforced co-rotation is never approached for reasonable field strengths. The magnitude of photospheric field required for an appreciable effect on the mass-loss rate is a few hundred gauss, which is potentially detectable. If the field is this large, however, the wind torque exerted on the star spins it down within a fraction of its main-sequence lifetime.

A question that is often raised about the radiatively-driven wind is whether radiative driving is sufficient, in the sense of being able to "get the wind going" without assistance from some additional force such as wave pressure, etc. This is really two questions: (1) Is another force necessary, in a steady-state wind, to drive the flow at large optical depth, where the force exerted by radiation pressure in the spectral line is negligible? and (2) Can radiation pressure create a wind in a star that is initially in a hydrostatic state? The answer to the first question is very simple. The force due to the spectral lines is quite large throughout the supersonic region and begins to diminish going inward from the sonic point where the flow velocity becomes comparable with the intrinsic linewidth (thermal velocity). In this subsonic region the outward force is provided by the gradient of gas pressure and only a slight excess of the pressure gradient over gravity is needed to accelerate the flow. This slight excess is the rarefaction that is the response of the deeper layers to the removal of the material above. In other words, gas pressure is the only force needed to "get the wind going" in the subsonic region.

The question of whether a radiative-driven wind will begin in an initially static star is more delicate. The answer given by Abbott (1982) is "yes" for O stars, and "it depends" for B stars — a static structure would not be disrupted by radiation pressure alone in the cooler and fainter B stars.

Another question frequently asked is whether inaccuracy of the Sobolev approximation (essential to the CAK theory) vitiates the conclusions about the unique regular solution and the eigenvalue property of the mass-loss rate.

This question is best answered by removing the Sobolev approximation and examining the changes in the wind properties. Such a comparison has been made by Castor and Weber (1985, in preparation), who repeated the comparison done by Weber (1981), but with refinements in the Sobolev wind theory so that only the Sobolev approximation itself could be the source of differences. The differences found were then quite small: the self-consistent wind models differed by no more than 15% in velocity structure or mass-loss rate.

The present status of agreement between radiatively-driven wind theory and observations of hot-star winds is this: For the O, Of, and B super-giant stars the calculated and observed rates of mass loss are in good agreement, with a similar dependence on stellar luminosity. There is a spread in the observed M vs. L relation that is greater than the spread predicted by theory, and also greater than observational error. This may be due to the effect of rotation or localized magnetic fields, or simply the effect of temporal and spatial fluctuations in the wind diagnostics. The theoretical relation between wind terminal speed and escape velocity is in satisfactory agreement with observation provided (1) the realistic line list is used, (2) the finite cone angle of photospheric radiation is taken into account, and (3) the "after-burner" effect of multi-line scattering is taken into account.

For B and Be stars the applicability of the radiatively-driven wind theory is problematical. The empirical M vs. L relation obtained by Snow (1981) for B stars appears to be an extension of that found by Garmany, Olson, Conti, and Van Steenberg (1981) for O stars, although the scatter is much greater. Since it does not appear that B stars lose *more* mass than implied by the extrapolated O star relations, there is no imperative to find a new mechanism to explain the amount they *do* lose. From a theoretical point of view, radiative driving is in a precarious state for the less luminous B stars. The theory fails unless there is at least one opaque driving line in the wind, so the mass loss should be at least L/c^2. The empirical relation falls to this value when the mass loss rate is about $10^{-10}\ M_{\odot}\ y^{-1}$, at M_{bol} = −4 to −5. Many of the B stars have mass loss rates below 10^{-10}, for which the radiative driving theory, at least in its simple form, would not apply. The picture of a one-fluid flow is also very suspect when the mass loss rate is low, since the two-body coulomb coupling between the driven ions, such as C^{+3} and Si^{+3}, and the protons and electrons becomes too weak to prevent outward flow of those ions with respect to the rest of the plasma; the Maxwellian distribution of those ions may also break down. Plasma instabilities will become critical for determining the state of the flow.

The state of the comparison between radiatively-driven wind theory and observation for Wolf-Rayet stars has changed recently with two important discoveries: The first is that multi-line scattering can provide mass-loss rates well in excess of the "single scattering limit," $L/v_{\infty}c$ (Friend and Castor 1983; Abbott and Lucy 1985). The second discovery is that at least one WR star, V 444 Cygni, is very hot; the temperature referred to its thermalizing radius is about 95,000 K (Cherepaschuk, Eaton, and Khaliulin 1984). Such a high effective temperature means that the bolometric correction is appreciably larger (in magnitude) than was supposed. The higher luminosity then inferred for the star reconciles the discrepancy between wind theory and observation, as demonstrated in a recent paper by Pauldrach et al. (1985). The striking disagreement between the effective temperature of V 444 Cygni and its apparent photospheric temperature is a manifestation of the very nonclassical structure of the Wolf-Rayet stellar atmosphere.

The observational manifestations of wind instabilities in hot stars are now well known: the presence of superionized species in the spectrum, such as O VI, and in cooler stars also N V and C IV; the existence of soft X-ray emission, which is also sufficient to explain the superionization; large-scale fluctuations in the Hα emission wings and in the absorption troughs of the UV resonance lines; the velocity fluctuations of ~500 km/s needed to explain the blackness of the absorption troughs; and, recently discovered, nonthermal radio emission from a sizeable minority of the O stars with winds (Abbott, Bieging, and Churchwell 1984). The theory of wind instabilities has also burgeoned, providing a great many candidate instabilities that may produce the disordered motion and shock waves that are the most natural explanation of the phenomena listed above. Not yet clear is the answer to the question: <u>which</u> instability(-ies) is (are) the important one(s)? Martens (1985) supplied a chart of essentially all possibilities. The analysis of them has been hampered by the lack of a unified approach, and by insufficient attention being paid to the <u>nature</u> of the instability, viz., "absolute" (also called modal or global) vs. "drift" (also called convective). (See Bers, 1983.) In essence, absolute instabilities grow in time at each fixed point in space, while drift instabilities grow in time also, but only in a frame that moves away from the region of the initial disturbance. Drift instabilites need a finite initial disturbance to do anything; absolute instabilities can grow from the most infinitesimal disturbance.

My own review of the instabilities in Martens' chart leads me to the conclusion that <u>all</u> instabilities considered so far are, in fact, drift instabilities, at least in the realistic limit that isothermal oscillations are assumed. If a small but non-zero cooling time is assumed, then absolute instability may exist for the acoustic and gravity modes in the optically-thin limit in the subsonic region, driven by density and temperature variations of the continuum radiation pressure, as suggested by Hearn (1972) and Carlberg

(1980). The growth rates are exceedingly small, however, and these modes may turn out to be stable in a global analysis. By far the most potent of the instabilities is the line-shape instability (the designation due to Carlberg) discussed by Lucy and Solomon (1970), MacGregor, Hartmann, and Raymond (1979), and Owocki and Rybicki (1984). This instability is weak in the subsonic region, but in the supersonic region the growth rate is quite large, so that a disturbance will amplify by a factor _e_ in being carried by the flow only a short distance — the Sobolev length, which is less than the velocity scale height by about a factor of the Mach number. The work of Owocki and Rybicki was criticized by Lucy (1984), but a careful calculation (Owocki and Rybicki, preprint) answering Lucy's objections gives a similar result to the earlier one with a somewhat reduced growth rate. Thus, the line-shape instability can amplify any disturbance present near the sonic point by _forty orders of magnitude_ by the time the flow has reached half-terminal velocity, unless the nonlinear regime has been reached!

At this time, we can make only conjectures about the nonlinear development of this instability. One likely supposition is that an acoustic-mode disturbance at the sonic point will quickly form a shock wave which will be driven by the radiation force and quickly become quite strong, at which point it will resemble one of the shocks in the periodic shock structure proposed by Lucy (1982). The growth rate of the line-shape instability is greatest for short wavelengths, so the velocity fluctuations in the inner part of the supersonic region should be quite disordered on the scale of the mean flow; amalgamation of the shocks may simplify the structure in the outer region. This large amplitude (~500 km/s) almost random fluctuating part of the velocity field would act like a turbulent velocity in its effect on the radiative transfer in the driving lines; in other words, it would increase the intrinsic line width and thereby lower the growth rate of the instability, producing linear rather than exponential growth.

What role would nonradial pulsation play in modulating, or otherwise interacting with, the wind instabilities? The first effect that comes to our attention is the shock wave inevitably generated in the atmosphere of a pulsating star: A finite amplitude velocity oscillation produces an acoustic wave that steepens into a shock in a distance that can be estimated from the frequency and amplitude of the oscillation and the sound speed and effective gravity in the atmosphere. For O or B star parameters, if the oscillation frequency is like that of the radial fundamental mode (period of a few hours) and the photospheric amplitude is about the sound speed, the shock would form roughly three scale heights above the photosphere. In other words, a shock would form <u>below where the sonic point would be in the wind of a nonpulsating star</u>. The wind flow time in the supersonic region is an hour or two, i.e., <u>less</u> than the pulsation period, so the wind should normally be able to adapt to the motion of the photosphere. The big effect we can expect is that the shock wave will provide a large initial disturbance for the line-shape instability to amplify. It may be that this large periodic driving term will inhibit the growth of disturbances that are out of phase with it, so that the one big shock per period of oscillation may dominate the velocity fluctuations in the wind. If this is <u>not</u> the case, then the influence of the pulsation on the wind would be secondary compared with the <u>in situ</u> disturbances.

There is also a possibility — but only a faint one! -- that the reaction of the wind on the photosphere of the star can help destabilize the stellar envelope against pulsation. If there were an absolute instability of the wind in the acoustic mode, which would have to be driven in the subsonic region since very general arguments indicate that all instabilities are drift in the supersonic region, then mechanical energy fluxes would be produced that would carry energy both outward and inward. The order of magnitude of these fluxes would be (growth rate of the instability) × (kinetic energy of pulsation in the wind). This can be compared with the normal stellar envelope damping, which is of order (stellar luminosity) × (relative radius variation)^2. These numbers can all be estimated, and if the optimistic growth rate of the line-shape instability is used together with a generous estimate of the wind kinetic energy, it is found tht the wind driving is comparable with the envelope damping. A number of objections can be raised against this mechanism (growth rate optimistic, line-shape instability inoperative in subsonic region, no correlation seen between pulsation and mass-loss rate) so that it cannot be considered a serious possibility. It does, however, indicate that the barrier of ignorance that allows the stellar envelope to pulsate independently of the wind, and vice-versa, is not as impenetrable as might sometimes be supposed. I think a pulsational stability analysis of stellar envelope and wind together will be a useful way of learning about the interactions of these two interesting regions of the star.

This work was performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48.

REFERENCES

Abbott, D. C. 1977, Ph.D. thesis, Univ. of Colorado (unpublished).

Abbott, D. C. 1982, Ap. J. 259, 282.

Abbott, D. C., Bieging, J. H., and Churchwell, E. 1984, Ap. J. 280, 671.

Abbott, D. C., and Lucy, L. B. 1985, Ap. J. 288, 679.

Bers, A. 1983, in Handbook of Plasma Physics, Vol 1, Basic Plasma Physics I, A. A. Galeev and R. N. Sudan, eds. (Amsterdam: North Holland).

Castor, J. I. 1979, in Mass Loss and Evolution of O-Type Stars, I.A.U. Symposium No. 83, P. S. Conti and C. W. H. De Loore, eds. (Dordrecht: Reidel).

Castor, J. I., Abbott, D. C., and Klein, R. I. 1975, Ap. J. 195, 157.

Cherepashchuk, A. M., Eaton, J. A., and Khaliulin, Kh. F. 1984, Ap. J. 281, 774.

Carlberg, R. G. 1980, Ap. J. 241, 1131.

Friend, D. B., and Castor, J. I. 1983, Ap. J. 272, 259.

Friend, D. B., and MacGregor, K. B. 1984, Ap. J. 282, 591.

Garmany, C. D., Olson, G. L., Conti, P. S., and Van Steenberg, M. E. 1981, Ap. J. 250, 660.

Hearn, A. G. 1972, Astron. Astrophys. 19, 417.

Lucy, L. B. 1982, Ap. J. 255, 286.

Lucy, L. B. 1984, Ap. J. 284, 351.

Lucy, L. B., and Solomon, P. M. 1970, Ap. J. 159, 879.

MacGregor, K. B., Hartmann, L., and Raymond, J. C. 1979, Ap. J. 231, 514.

Martens, P. C. H. 1985, in The Origin of Non-Radiative Heating/Momentum in Hot Stars, A. B. Underhill and A. G. Michalitsianos, eds., NASA CP-2358, p. 226.

Owocki, S. P., and Rybicki, G. B. 1984, Ap. J. 284, 337.

Panagia, N., and Macchetto, F. 1982, Astron. Astrophys. 106, 266.

Pauldrach, A., Puls, J., Hummer, D. G., and Kudritzki, R. P. 1985, Astron. Astrophys. 148, L1.

Snow, T. P. 1981, Ap. J. 251, 139.

Weber, S. V. 1981, Ap. J. 243, 954.